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RAPHAEL, A EUROPEAN PROJECT FOR THE DEVELOPMENT OF HTR/VHTR TECHNOLOGY FOR INDUSTRIAL PROCESS HEAT SUPPLY AND COGENERATION

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ABSTRACT

Since the late 1990s, the European Commission is supporting the HTR-TN partnership work on the development of HTR, that resulted in confirming HTR high potential in terms of safety (inherent safety features), environmental impact (robust fuel without significant radioactive release), sustainability (potential suitability for various fuel cycles), and economics (high efficiency, simplifications arising from safety features). In April 2005, a new 4-year Integrated Project on HTR/VHTR (RAPHAEL – ReActor for Process Heat And ELectricity) was started as part of EURATOM 6th Framework Programme (FP6), with the 33 partners from industry, R&D organisations and academia. The main priorities of the project are the increase of performances (temperature 800-1000°C, and burn-up up to 200 GWd/tHM) and the adaptation of technologies to the needs of heat supply for industrial processes, in line with the conclusions of the Generation IV roadmap: search for advanced materials and fuel for higher operating temperatures, development of components required for heat applications (intermediate heat exchanger and high power helium circulator), examination of the specific issues raised by higher performances and industrial process heat applications in the HTR safety approach developed during the 5th Framework Programme (FP5). In parallel, some of the generic work started in FP5 on base HTR/VHTR technologies and computer tools still needs to be continued and complemented, when lacks have been identified. This is the case for code qualification, with comparisons calculation / experiment, on the basis of data recovered from existing tests or from new ones performed within RAPHAEL (isotopic analysis of a pebble irradiated to very high burn-up, irradiation of fuel material samples, PIE and heat-up tests of fuel irradiated during FP5, air ingress test). This is also the case for fuel modelling, further developed with a whole core statistical approach, for fuel back end, with the continuation of long term leach tests started in FP5 and for the graphite irradiation of FP5, which will be restarted in order to pass the turn-round point, while a new one will allow getting higher temperature data (~ 950°C). A participation of RAPHAEL in the future VHTR projects of the Generation IV International Forum (GIF) is planed.

INTRODUCTION AND OBJECTIVES

In the context of worldwide depletion of fossil fuel resources, uncertainties on supply, and CO_2 reduction objectives, Europe invests in R&D to ensure the viability of nuclear fission as a future energy option. Continuing the work initiated in several smaller projects supported by the European Commission since 1998, the European High Temperature Reactor Technology Network (HTR-TN) proposed the RAPHAEL Integrated Project and put together a consortium of 33 partners from 10 European countries for its execution (see composition in last part of the paper). RAPHAEL, which started in April 2005, with duration of 4 years, addresses the viability and performance issues of an innovative system for nuclear systems of next generation, the modular High and Very High Temperature Reactor (HTR/ VHTR), which shall supply both electricity and process heat.

At present, nuclear fission produces almost exclusively electricity, which, however, accounts for only 16% of the energy consumed worldwide, 79 % of the remaining energy consumed in the world being obtained by burning fossil fuel [1]. Therefore nuclear energy cannot contribute significantly to reduce the dependence on fossil fuel supply and the global warming risk by addressing only electricity generation. Addressing the area of process heat for industry, in particular (but not only) for producing secondary energy carriers like hydrogen or synthetic hydrocarbon fuel, should be a key strategic objective for nuclear energy.

Because it produces heat at high / very high temperature using a smaller reactor with a very robust safety concept, the HTR/VHTR system opens potential application to a wider range of competitive applications than light water reactors. These applications include medium-sized electricity production or process heat generation e.g. for CO_2-free hydrogen production, for chemical processes (oil refining, fertilizers etc.), and the use of waste heat for lower temperature applications such as desalination or district heating. Therefore a central concern of RAPHAEL will be heat and power applications of HTR/VHTR in consistence with the objectives of sustainability and safety of next generation power plants.

The HTR/VHTR also features inherent safety, waste minimisation approaches, fuel cycle flexibility and cost effectiveness – all key assets regarding public acceptance of nuclear fission and its positive impact on the economy, the environment, and the security of energy supply in line with Generation IV roadmap goals [2].

The development of modern HTR/VHTR goes far beyond the characteristics of past and present HTR operating reactors, both with pebble bed cores (AVR, THTR, HTR-10) and block type cores (Peach Bottom, Fort Saint Vrain and HTTR) and is rather challenging: the modular design, with its inherent safety features adopted by all present prototype projects, has not been used for large scale reactors yet; the temperatures aimed at, in the range 800-1000°C, require materials with higher performances than those used in past HTRs, which need specific qualification. Operating HTR fuel in this range of temperature with a target burn-up (150-200 GWd/tHM) higher than in previous projects is beyond existing industrial experience. Moreover there is no experience of coupling a HTR with a large scale industrial process heat application, even at lower temperature. For such an application, a large heat exchanger (Intermediate Heat Exchanger – IHX) with a capacity of heat transfer of several hundreds of megawatt, operating at high or very high temperature, is necessary. It is far beyond the present industrial experience. Furthermore this heat exchanger must be compact in order to be enclosed into a steel vessel, which is part of the pressure boundary of the primary circuit. Therefore plate heat exchanger designs that are much more compact than tube heat exchanger designs are favoured. But again the power level, the high temperature and the loads imposed by pressure and temperature transient conditions of these heat exchangers are beyond industrial experience. Such performances will be possible only with advanced high performance materials. All these conditions make the IHX the most challenging component in the development of modern modular HTR/VHTR. It should be added that the search for higher performances will require extending the qualification domain of design computer tools and developing some of them for more precise description of the phenomena and therefore lower margins for uncertainties.

Therefore the development of modern modular HTR/VHTR will require a strong R&D support. The ambition of RAPHAEL is to bring such a support and therefore to be a leading force for this development.

CONTEXT

The FP5 European HTR programme

RAPHAEL is not starting from scratch. After a small project of the 4th Framework Programme assessing the potential of HTRs for future industrial applications, the HTR R&D was actually launched with 10 FP5 coordinated contracts, which addressed key feasibility issues and base developments. Very significant results were obtained, on the basis of which RAPHAEL is building the development of technologies for advanced HTR/VHTR. The results, which are the most significant for the present follow-up, must be reminded [3].

Reactor physics

The results of the international benchmark of HTTR and HTR-10 first criticality have shown very large discrepancies in reactivity calculations between experimental data and calculation results provided by many different codes, which, themselves, were moreover rather scattered. The work performed during FP5 allowed understanding the physical reasons for these discrepancies and improving the modelling of HTR specific reactor physics features (double heterogeneity, neutron streaming, neutron spectrum discretisation…) [4]. It allowed the partners obtaining a qualification of the reactivity calculations with their codes.

Fuel

A systematic comparison of the different empirical laws describing the behaviour of the fuel materials under irradiation and of the experimental data supporting these laws allowed selecting the most relevant data and laws to be used in fuel performance codes and identifying the areas where additional work is necessary for improving the quality of HTR fuel modelling [5].

The state-of-the-art technologies for TRISO fuel fabrication have been recovered through experimental work:

- UO_2 spherical kernels have been produced with a sol-gel process,
- Good quality TRISO coating have been obtained on dummy kernels with a Chemical Vapour Deposition process (figure 1)

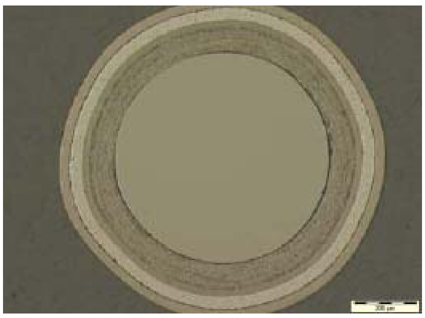

Figure 1: Buffer, IPyC, SiC, OPyC coating layers on a dummy kernel, CEA Grenoble

On the basis of this work, the French CEA could build a pilot line for re-fabricating HTR coated particles in Europe.

Moreover the first tests of fabrication of TRISO particles with an advanced ZrC coating in replacement of SiC were performed. Such a coating has the potential of improving HTR fuel performances in normal and accident conditions.

It has been demonstrated that the German state-of-the-art fuel could reach on an industrial basis a burn-up of 80 GWd/tHM and withstand accident heat-up transients up to 1600°C without any significant radionuclide release. Moreover a few tests have shown that there are significant margins for higher performances of such fuel. The objective of the FP5 HTR fuel irradiation programme was to explore the behaviour of state-of-the-art HTR fuel with the higher performance targets aimed at in most of the present HTR/VHTR projects [6]: a first irradiation in HFR (Petten, Netherlands) of state-of-the-art HTR fuel (from past German fabrication) in VHTR conditions (helium at 1000°C, 160 GWd/tHM), has been completed end of 2005. Fission gas release was monitored, which did not allow detecting any significant fuel failure. The good behaviour of the fuel will have to be confirmed by the ongoing PIE. Another irradiation for exploring the fuel behaviour at even higher burn-up (200 GWd/tHM), but at a lower temperature (helium at 850°C), is under final preparation work.

Now for demonstrating the acceptability of the fuel for modular HTR/VHTR, its accident behaviour must be tested: for that purpose a heat-up facility of irradiated fuel, with on-line fission product release monitoring, has been constructed in an ITU hot cell (figure 2). Its first tests have been performed [7], using already irradiated pebbles recovered from the former German programme.

Materials

There is an incentive for use of a material with improved temperature performance compared to PWR vessel steel in order to improve HTR thermal efficiency and to obtain margins toward reactor vessel failure in accident conditions. Different materials have been examined and the Modified 9Cr1Mo steel has been identified as the best candidate. An irradiation of a thick welded joint of this material has been completed up to a fast fluence equivalent to 60 years of operation and PIE have shown no significant change in the mechanical properties both for the base material and for the welded zone [8].

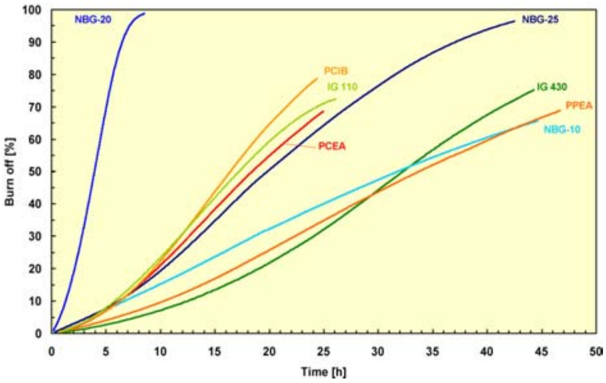

Figure 3: oxidation rate of the different graphites considered in FP5 at 650°C in air

As the graphite grades used in former projects are no more available, the first phase of an irradiation of different presently available commercial graphite grades has been performed at 750°C, in order to select the most appropriate one for HTR applications. This programme will be continued in RAPHAEL. Tests were also launched on the oxidation behaviour of the same grades, showing that all but one had a similar behaviour (figure 3). This grade (NBG-20), which showed a high sensitiveness to oxidation, is removed from the list of potential candidates for HTR applications, but further investigations are made for understanding the reasons for its particular behaviour.

Components

FP5 HTR projects were focused on direct cycle system with a vertical shaft helium turbine coupled to the

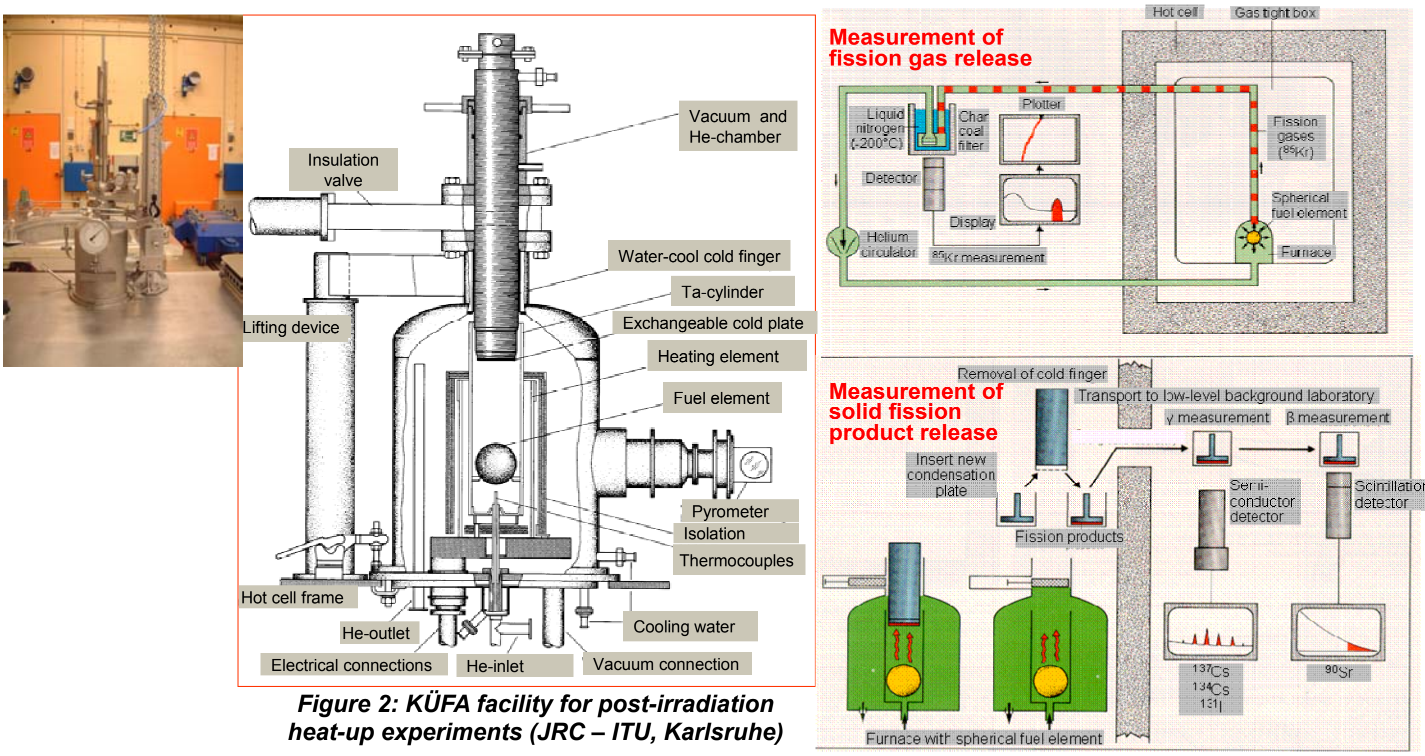

Figure 2: KÜFA facility for post-irradiation heat-up experiments (JRC – ITU, Karlsruhe)

reactor in the primary circuit and supported by magnetic bearings, as this was the configuration of the main industrial projects when these FP5 projects started. But the work performed in FP5 allowed identifying limits of this concept for the turbine:

- No existing industrial material could be found for withstanding the turbine operating conditions (temperature of at least 850°C required for a good thermal efficiency and high stresses generated by turbine rotation) without cooling the disks and blade feet.
- With the most promising candidate material selected for disks, Udimet 720, the feasibility of manufacturing disks is limited to a diameter of 1 m.

These results are constraining the design of the turbine and limiting the efficiency of the system [9].

Moreover due to safety considerations (missile risk in case of deblading accident) and to limitation in the acceptable load for catcher bearings, which replace active magnetic bearings in case of loss of electric supply, the vertical layout of the turbine must be reconsidered. It is interesting to note that designers of PBMR and GTHTR-300 reached the same conclusion. With the reconsideration of the vertical lay out of the turbine, its advantage in terms of reactor building compactness and cost effectiveness will be lost.

HTR waste management

A study of the behaviour of irradiated HTR fuel in the geo-chemical environment of a final disposal has been initiated: the (radio-)chemical interactions of each fuel barrier with different possible geo-chemical environment is tested separately in long term experiments. With the input of test results, mathematical models of these interactions are developed and integrated into a computer code. With this code, a preliminary calculation have shown a lifetime of an irradiated TRISO particle larger than 10 000 years. This first estimation will have to be confirmed in RAPHAEL by continuation of the tests on longer periods of time and by launching new more representative tests.

Safety approach

HTRs have unique inherent safety features (leak-tightness of the fuel up to very high temperature (~ 1600°C), strongly negative temperature coefficient, very large thermal inertia, chemical inertia of the coolant…) that allow their safety design to be based on the natural behaviour of the system ("modular" design), if the power of the reactor is low enough (no more than several hundred megawatts): in accident conditions, the fission reaction stops as soon as the temperature increases and the decay heat can be removed from the reactor vessel only by thermal conduction and radiative heat transfer, without requiring operation of engineered safety systems.

The internationally accepted standards, principles and methodologies (e.g. IAEA Safety Guides, OECD/NEA recommendations) have been applied to modular HTRs in order to define a safety approach taking full benefit of their inherent safety features. The objective of this approach is to obtain a drastic simplification in the reactor safety design, while providing a convincing demonstration of safe behaviour in any condition [10]. It is, for instance, shown that, while keeping the same high level safety requirements (defence-in-depth, multiple physical barriers, radiological release limit target, etc) as for other types of systems, it is possible

- To keep the core in a safe conditions during a loss of coolant accident without operation of any dedicated engineered active or passive safety system,
- Due to the exceptional robustness of the first barrier (fuel structure), to secure the confinement of radioactive releases with less demanding requirements on the third barrier (no resistance to internal pressure),
- To minimise the number of safety classified systems.

Interfaces with other European projects

RAPHAEL develops tight links with related FP6 projects to maximize synergies. HTR-TN serves as the platform for the coordination between the various projects.

Crossed specifications, regular interface meetings, balanced exchanges of results, and joint participation of several partners are key to mutual benefit with the following projects:

- Materials: contributing in the Integrated Project ExtreMat, together with partners from fusion and non nuclear industrial and research sectors, to the development of advanced materials under extreme conditions, allows benefiting from advances of these sectors in the fields of composites, ceramics, graphite and high performance thermal barriers,
- Hydrogen production: cooperation with HYTHEC (HYdrogen THErmochemical Cycles) allows developing consistent solutions both for the nuclear plant and a hydrogen production plant based on thermo-chemical processes,
- Gas-Cooled Fast Reactor: cooperation allows developing synergies with this other Generation IV concept in the fields of material, component and fuel development.

Another project addressing HTR fuel cycle issues, PUMA, most particularly actinide recycling, is just about to start and will generate further synergies.

International cooperation

Partners of the European FP5 HTR programme actively participated in the Generation IV roadmap. Now EURATOM being member the Generation IV International Forum (GIF), the RAPHAEL partners are interested in providing results from the Project as EURATOM contributions to the GIF VHTR projects, as far as there is a qualitative balance with complementary results they receive from other GIF partners. RAPHAEL representatives systematically participate in the GIF VHTR provisional Steering Committee and Project Management Boards and they actively contribute to the definition of the GIF VHTR work programme. Depending on the results of these discussions, the work programme of RAPHAEL may be tuned to complement the contributions of other GIF partners and to avoid useless duplications.

Cooperation with Russia is organized via the International Science & Technology Centre (ISTC), which receives funds from the European Commission for supporting HTR projects in Russian laboratories. There are already relations with OKBM in the field of materials and component development. A test in the zero power ASTRA reactor of Kurchatov Institute is being presently discussed in which, if finally accepted, RAPHAEL will actively participate (discussion of the test programme, selection of the data to be acquired, review of results, etc).

Cooperation with the OECD Nuclear Energy Agency (NEA) is also foreseen, by proposing benchmarks planned by RAPHAEL to be organised in the larger frame of the Agency. RAPHAEL partners are also actively involved in relevant IAEA benchmarks, bringing their work to the Project.

The USNRC already participated in meetings of the FP5 safety project, in which the elaboration of the HTR specific safety approach was discussed, and will continue to interact with RAPHAEL. IAEA will also be associated to the discussions.

PROJECT PROGRAMME AND FIRST ACTIONS

Most of the work programme of RAPHAEL is in the continuity of the FP5 projects, with nevertheless

- An emphasis put on the search of solutions for performance improvements (higher temperature, higher fuel burn-up) – the VHTR orientation,
- A focusing on the potential for heat applications of HTR/VHTR, in line with the Generation IV roadmap conclusions [2], which pointed out that the specific mission of this type of reactor, was, beyond mere electricity generation, to provide sustainable CO_2 free industrial process heat.

For fulfilling this new objective, RAPHAEL addresses the development of the key components for heat applications and of the materials required for these components.

As mentioned above, the feasibility of a consistent coupling between the reactor and thermo-chemical processes for hydrogen production is addressed jointly with the European HYTEC project. Beyond the joint work with HYTEC, the coupling with high temperature electrolysis will also be addressed.

It was decided right from the beginning of the project, to get boundary data from actual reactor projects, to make the RAPHAEL R&D globally consistent and useful for industrial applications. In continuation with FP5 options, ANTARES project from AREVA NP and PBMR are considered as reference designs. For the time being, required data are more easily available from ANTARES, but PBMR data would also be welcome. Anyway, as it was already the case during FP5, the R&D actions are defined on a case by case basis in order to satisfy the needs of both designs. They can

- Be generic (e.g. qualification of computer codes),
- Complement existing data (e.g. performing NACOK air ingress tests for a block type core, as several tests for pebble bed reactors have already been performed),
- Satisfy the needs of the most demanding design (e.g. the qualification of a vessel material for a high core inlet temperature (> 350°C) without vessel dedicated cooling).

The continuous integration of technical findings of the project will enable performing trade studies on key design options and assess the impact of R&D results on design.

RAPHAEL addresses the following areas:

Material Development

The objectives are, based on results from the FP5 projects HTR-M and HTR-M1,

- To enhance the database of mechanical properties of modified 9Cr1Mo steel: creep tests will be performed at 450°C (to complement the tests already performed at 550°C) on the material irradiated during FP5 and large scale tests will be launched.
- To complete the graphite irradiation behaviour data to full fluence levels and to higher temperature range (figure 5), in order to select the most appropriate grades for HTR/VHTR application, to investigate the possible benefit of a recovery of thermal conductivity in accident conditions and to develop microscopic models for the prediction of property changes under irradiation,
- To select materials for the highest temperature components: metallic for the IHX (nickel base alloys) and carbon-carbon composites for control rod claddings,
- To define Codes & Standards and design guidelines and procedures for application to new materials under development in HTR/VHTR conditions.

First actions

Creep tests of the mod. 9Cr1Mo samples irradiated in FP5 have been specified [11].

On the other hand, it appears that the creep mismatch, existing in mod. 9Cr1Mo welds between the base metal, the heat affected zones and the welding itself, may produce geometry size-effects: small-scale specimen usually employed for laboratory creep tests may have different creep strength from large parts. Finite element calculations allowed CEA showing indeed that results from usual small scale laboratory scale tests are very conservative and defining the main parameters of tests for confirming this effect [12]. These tests will be performed in Cadarache AIRBUS facility, starting in 2007, on large diameter non irradiated mod. 9Cr1Mo shells with circumferential narrow gap gas tungsten arc welding in accident conditions (625°C) (figure 4).

Figure 4: AIRBUS creep test in CEA (450-625°C, 150 bars)

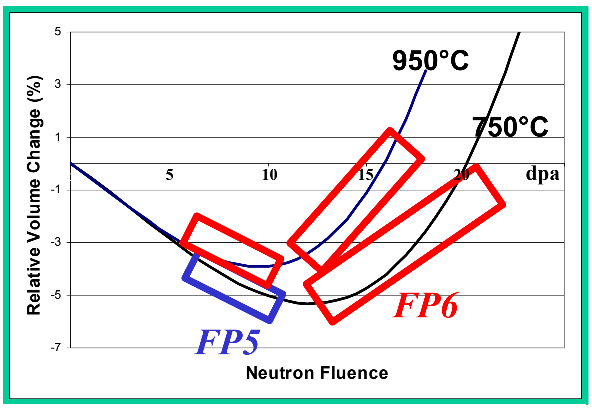

Figure 5: graphite irradiations in FP5 and FP6

At the end of FP5 HTR graphite work package, a set of samples of 8 different grades were irradiated to a maximum of about 10 dpa. The experience obtained through FP5 corrosion tests allows eliminating NBG-20 in the follow-up programme. 2 newly available grades, NBG-18 selected for PBMR and NBG-18, rather similar but with a 2 times smaller filler grain that would make it more suitable for the fine structure of prismatic blocks, have been added to the other grades already tested during FP5 (see in table 1 the graphite grades selected for RAPHAEL programme). An irradiation is launched (starting August 2006) with 80 pre-irradiated samples from FP5 and 80 fresh specimen in order to reach the target maximum dose of 25 dpa (figure 5). Another irradiation is launched with the same grades at 950°C (starting May 2006) [13]. Pre-irradiation characterisation of the samples has been performed (dimensions, Young's modulus, coefficient of thermal expansion and thermal diffusivity coefficient). The irradiation at 750°C and related PIE will be completed in 2009 and the irradiation at 950°C and related PIE end of 2010 (beyond the end of FP6 RAPHAEL project), with intermediate data at 10 dpa released in 2008.

Table 1: graphite grades of the RAPHAEL irradiation programme

Grade	Manufacturer	Coke	Process
PCEA	Graftech	Petroleum	Extrusion
PPEA	Graftech	Pitch	Extrusion
PCIB-SFG	Graftech	Petroleum	Iso-moulding
BAN	Graftech	Needle	Extrusion
NBG-10	SGL	Pitch	Extrusion
NBG-18	SGL	Pitch	Vibro-moulding
NBG-25	SGL	Petroleum	Iso-moulding
NBG-17	SGL	Pitch	Vibro-moulding
IG-110	Toyo Tanso	Petroleum	Iso-moulding
IG-430	Toyo Tanso	Pitch	Iso-moulding

A heat-up experiment is being planned to determine the recovery of thermal conductivity (TC) with temperature on irradiated graphite, as graphite forms a major part of the heat removal path following a serious accident. A relatively small amount of fluence can reduce the TC of the graphite by a factor of 10-20, which could have a serious effect on the heat removal rate from the fuel, and hence the peak temperatures reached. It is planned to perform this heat-up experiment on pre-irradiated graphite from the 750°C phase 1 experiment, to see if some benefit can be claimed from the recovery in TC for the safety case. If a significant benefit can be shown, this could bring operating margins and a significant help for the VHTR licensing case. Currently the safety case needs and experimental parameters are being reviewed before planning the heat-up phase in shielded facilities.

Component development

The key component for a flexible use of HTR/VHTR for heat applications and possibly for electricity generation

Figure 6: tubular IHX 10 MW mock-up in the former German programme

(in case of indirect cycle) is a large scale heat exchanger (IHX) removing the heat from the primary circuit and providing it for the application in the secondary circuit. The tubular helical concept inherited from the past German developments (figure 6) will be assessed and compared through thermo-mechanical and thermo-fluid dynamics analyses to the plate concept. Elementary forming and welding tests will be performed for the tubular concept with the candidate Ni base alloys considered for the IHX.

Figure 7: HEFUS 3 helium loop (ENEA, Brasimone)

With ENEA joining the project, heat transfer tests of small plate IHX mock-ups are considered in its helium loop HEFUS 3 (figure 7). These tests, planned to be performed early 2007, will provide the first data for heat transfer in helium (and possibly helium-nitrogen for the secondary side of the ANTARES concept of AREVA NP) with representative geometry and Reynolds number. For the time being it is considered that uncertainty on the heat transfer coefficient is

Figure 8: FLP 500 facility, IPM Zittau

about 50%, with a direct impact on IHX size. Even if the HEFUS 3 operating temperature is only 500°C, a significant benefit is expected from such tests.

Based on the past German HTR and British AGR experiences, the conceptual design of the primary helium circulator for a 600 MWth reactor will be performed. The past HTR experience is limited to a circulator power of 5 MW, where the need is now between 10 and 15 MW. The circulator will be supported by active magnetic bearings. The circulator rotor dynamical response to thermal and mechanical loads will be validated on the test facility FLP 500 of IPM Zittau (figure 8).

The design of other components (helium-water heat exchanger, isolation valve) will be assessed, as well as a concept of pre-stressed cast iron vessel.

The acquisition of data from the helium loop which was coupled to a conventional power plant in Oberhausen in Germany, started during FP5, has been finalised with the owner of the plant, the EVO utility. Technological data on the design and operational behaviour of components at high temperature in helium atmosphere are therefore available with RAPHAEL as well as thermo-fluid dynamics data acquired during transient tests of the loop, which will be very useful for benchmarking of transient analysis codes.

The tribological tests performed in FP5 will be extended to VHTR conditions.

Fuel technology

On the basis of the FP5 fuel irradiations, the R&D is focused on the understanding of failure mechanisms and on determining the limits of state-of-the-art fuel, as well as on potential further performance improvements:

- PIE and heat-up tests performed on the fuel irradiated during FP5 for investigating the behaviour and possible failure mechanisms of the state-of-the-art fuel in normal and accident VHTR conditions (in very high burn-up and high / very high temperature conditions). The final results will be obtained in 2008 after transportation of the fuel irradiated during FP5 in ITU for heat-up test.
- Development of a fabrication process for an alternative kernel composition (UCO), with a potential for decreasing the CO pressure built-up in the particle, in order to be able to reach a higher discharge burn-up.
- Based on first very preliminary tests performed on ZrC coating during FP5 (figures 9 and 10), which showed the need for improvements in particular in the stœchiometry of the layer, development of a fabrication process for this alternative coating layer, which remains stable at higher temperature than SiC, and therefore should provide increased margins in accident conditions.
- Investigation of the feasibility of a weak irradiation method in order to control the quality of fuel manufacturing.

Moreover, based on the fuel particle models established in FP5, further actions for improving fuel modelling capabilities are planned:

- An "analytic irradiation" in HFR for measuring the evolution of coating material properties as a function of the integrated fluence, with samples coming from the fabrication process implemented by CEA on the basis of FP5 achievements [3].
  The property laws of fuel materials, that will be drawn from this test, will not only be more accurate than existing laws based on old data presently used in fuel modelling, but also more relevant for the modelling of the presently manufactured fuel.
- Development of fission product release modelling and statistical methods for integration of the individual behaviour of thousands of particles within a fuel element and then of billions of particles in the whole core.
- Continuation of code benchmarking, started in FP5, with the acquisition of new experimental data, in order to improve the qualification of the partners' fuel performance computer tools.

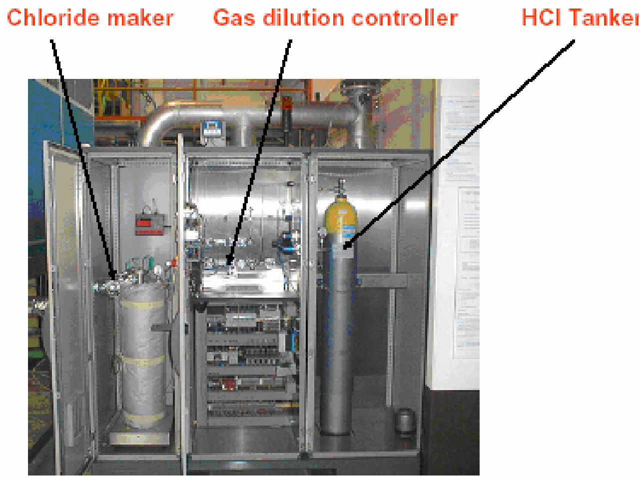

Figure 9: $ZrCl_4$ equipment for ZrC coating

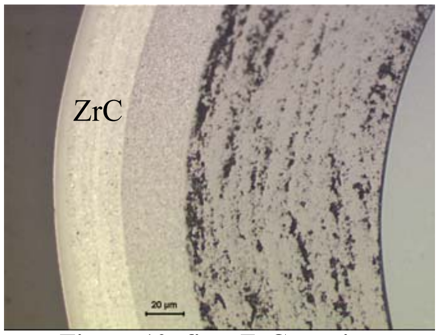

Figure 10: first ZrC coating

<u>First actions</u>

The samples for the "analytic irradiation" are being presently defined as well as the PIE: geometrical parameters, density, micro-structural examination and anisotropy will be measured in order to correlate the strains with stresses and with the micro-structure and anisotropy evolutions. The irradiation is planned for 2008-2009.

Sensitivity studies have been performed with the ATLAS code of CEA on the influence of different types of uncertainties (manufacturing parameters, irradiation conditions, behaviour laws) on the evolution of a coated particle under irradiation [14]. It appears that the stress in the SiC layer is subject to a large uncertainty, mainly due to uncertainties in particle manufacturing parameters – in particular the kernel radius, buffer thickness and porosity. The uncertainty on the stress in the pyrocarbon layers is small.

Core physics

Pursuing earlier work within FP5 projects, which allowed improving and validating the partners' reactivity calculation schemes, the general objective is the improvement in code qualification for reactor physics and safety analysis through comparison with experimental data for both pebble bed and prismatic block type designs. This comprises modelling of hot full power conditions with coupled neutronics and CFD codes both for static and transient conditions. Calculations will be benchmarked against experimental data from the AVR reactor, from HTR-10 and possibly from the new high temperature test in ASTRA presently under consideration for funding by ISTC. Moreover there will be in 2007 an isotopic analysis of one of the pebbles which reached very high burn-up (160 GWd/tHM) in the FP5 VHTR fuel irradiation as soon as this pebble is transported to ITU, where the analysis will be performed. A benchmark of reactor physics calculations of the HFR irradiation against results of this analysis will be performed, in order to validate burn-up calculations in the partner's calculation schemes.

Fuel cycle back-end

The studies on fuel cycle back end have the following objectives:

- To establish a list of requirements for waste management on the basis of regulations in force in different countries,
- To characterise HTR spent fuel wastes,
- To establish schemes for HTR spent fuel conditioning,
- To continue the long term tests on the behaviour of the different UO_2/SiC TRISO particle materials in disposal conditions started during FP5 and to start additional testing for assessing the performance of UCO kernels and ZrC coating,
- To continue developing models on spent fuel performance started during FP5.

First actions

The separation of coated particle from their graphite matrices for disposal would have two advantages:

- A strong volume reduction,
- A better conditioning for delaying interactions of the fuel with aqueous phases present in the geological repository, in comparison with the graphite embedding of particles in compacts, as the graphite porosity opens a path for water penetration, as shown in FP5.

Different conditioning matrices have been assessed.

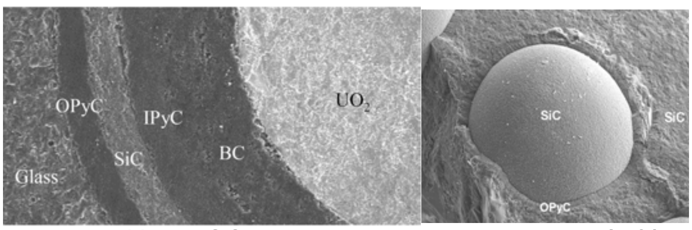

Figure 11: TRISO particle embedded in glass (left) and SiC (right)

The conclusion is that SiC is the best candidate. Nevertheless the thermodynamic stability of oxide matrices should also favour their selection as promising candidates [15].

The feasibility of conditioning processes with SiC and glass is also investigated. First results have already been obtained, showing good bonding of the matrix with coated particles (figure 11) and no cracks or bubbles in the matrix.

Safety

The elaboration of a safety approach started in FP5, taking due account not only of existing licensing frameworks, but also of specific inherent safety features of HTRs. It will be continued and will address the safety issues raised in general by heat applications and in particular by the coupling of a VHTR with a hydrogen production plant. The developments made in RAPHAEL on these topics and on all other safety related issues (e.g. safety aspects of fuel development) will be confronted with the point of view of different Safety Authorities and IAEA: they will participate in a Safety Advisory Group created by the Project, which will regularly review its work.

In order to contribute to their qualification, the transient analysis computer tools of RAPHAEL partners will be benchmarked for various configurations including direct/indirect power conversion, combined heat and power generation and available experiments from various loops or reactors. The first benchmark cases have been defined: data from the EVO loop and transients of the HEFUS 3 loop (see component development).

The existing experimental data and phenomenological knowledge on radioactivity source term and transport are reviewed in view of possibly defining further tests for complementing existing data and possibly improving modelling of chronic and accidental radio-contaminant transport and release.

Several air ingress experiments have already been performed is in the NACOK facility (figure 12) of the Forschungszentrum Jülich (FZJ) for pebble bed reactors, in order to understand and quantify the overall coupling of phenomena (graphite oxidation, natural convection…) in such events. In complement to these tests one or possibly two tests will be performed (the first one in 2007) in the frame of

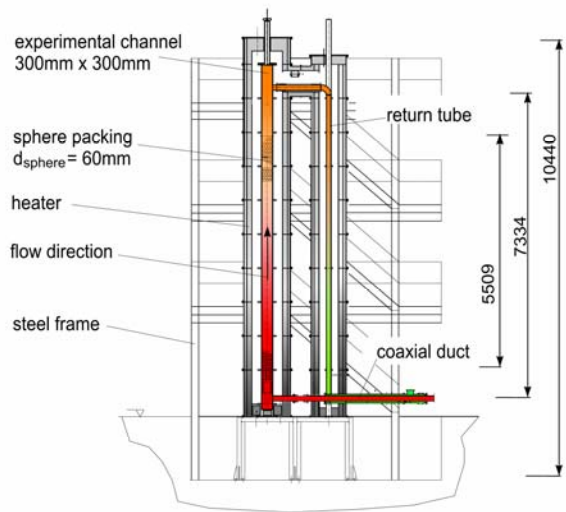

Figure 12: the NACOK facility

RAPHAEL project for a block type core configuration.

PROJECT CONSORTIUM

The RAPHAEL project is coordinated by AREVA NP. The partners' consortium is characterized by its wealth in diverse and complementary industrial and research expertise:

- Nuclear engineering companies (Ansaldo Nucleare (Italy), AREVA NP, BNFL, Empresarios Agrupados (Spain), AMEC NNC (UK), Serco Assurance (UK) and VUJE (Slovakia)),
- Leading companies in nuclear fuel industry, AREVA NC (fuel cycle), AREVA NP (fuel manufacturing), BNFL, as well as Belgonucléaire (with experience in manufacturing HTR fuel),
- Utilities (EdF and Suez-Tractebel),
- Organisations involved in the former German programme (AREVA NP GmbH, AVR GmbH and FZJ) and in other types of graphite moderated reactors (NNC),
- Two major worldwide graphite manufacturers, SGL and UCAR/GrafTech,
- Specialised industrial partners involved in the design and manufacturing of components: AREVA NP with its unique experience in manufacturing very large pressure vessels, Jeumont, a subsidiary of AREVA NP, manufacturer of the coolant pumps of French PWRs, for the gas circulator, and Société de Mécanique Magnétique (S2M), world leader in the field of magnetic bearings,
- Most of the European nuclear research organisations featuring long-standing expertise in various technologies:
    - CEA (France) which, together with AREVA NP and EdF, performs the largest national HTR/VHTR R&D programme in Europe,
    - FZJ, which was the focus of R&D in the former German HTR programme, keeping alive the legacy of German HTR technology with still active experts advising several present HTR projects in the world, and a few unique HTR dedicated research facilities, still operational,
    - The European Commission's Joint Research Centre (JRC) with the large hot laboratory of ITU, Karlsruhe, and irradiation facilities for fuel and materials in the HFR Petten, which since the 1970s which played a key role in the German HTR fuel qualification programme,
    - ENEA (Italy), NRG (The Netherlands), NRI Řež (Czech Republic), PSI (Switzerland), SCK-CEN (Belgium), providing their nuclear research capabilities and test facilities (such as material irradiation reactors, hot laboratories or test loops) and the Von Karmann Institute, providing its expertise in fluid dynamics for the circulator design,
- Six universities and engineering schools based in different countries, Delft University of Technology (The Netherlands), École des Mines de Nantes (France), University of Stuttgart and the University of Applied Sciences Zittau-Görlitz (Germany), University of Pisa (Italy), and the University of Manchester (UK), involved in education and training, beyond technical contributions from their laboratories.

CONCLUSION AND OUTLOOK

After the first recovery and advances in HTR technology provided by the HTR-TN partnership during EURATOM 5th Framework Programme, RAPHAEL is a step forward towards the technology of next generation HTR/VHTR. It is well embedded in a network of related international industrial and R&D projects, e.g. French AREVA NP ANTARES project and, expectedly, the future GIF VHTR projects.

While RAPHAEL partners are ready to rely on contributions of international partners in some areas, they endeavour to build a European leadership in some selected areas of the technology. Beyond the unique legacy of the former German programme kept alive and enriched by HTR-TN partnership since the beginning of the 2000s, this leadership is already recognised internationally, for instance in the field of HTR fuel irradiation, where there is an interest of non-European partners to participate in the "analytical irradiation" in HFR or in the field of HTR specific waste management.

For RAPHAEL partners, the next step should be an involvement for the development of a HTR/VHTR demonstrator for a combined heat and power application. Whether this should be the development of a European demonstrator with an international participation or a European participation in an international project, this new step should imply a change of scale in the effort. HTR-TN strives after convincing European stakeholders that such an effort is necessary for Europe to keep its leading role in nuclear energy towards the next generation. The period of the 7th Framework Programme (2007-2013) is expected to see such new step forward. As during FP5 and FP6, different key design options were explored, pebble bed core or block type core, direct or indirect cycle, cooled or non-cooled vessel, etc., the European partnership will be able, with a continuing support of European R&D during FP7 and with the contribution of European national HTR/VHTR programmes, to select during FP7 the most appropriate design options for the demonstrator and to start its preliminary design whichever design options are selected.

Further information can be retrieved on http://www.raphael-project.org.

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